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# Associations between measures of gait stability, leg strength and fear of falling



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## ABSTRACT

Fear of falling (FoF) in elderly frequently leads to decreased quality of life. FoF is suggested to be associated with changes in gait quality and muscle strength with aging. The aim of this study was to determine whether gait quality and maximal voluntary torque (MVT) of knee extensor muscles are associated with FoF. We hypothesized that high between-stride variability and local divergence exponent (LDE) of trunk kinematics in gait are associated with higher FoF in non-fallers, but not in fallers. Moreover, we hypothesized that knee extensor muscle strength is associated with a high variability and LDE of trunk kinematics during gait.

134 four adults, aged 62.4 (SD 6.2) years agreed to participate. FoF was assessed on a 10-point numerical rating scale. Subjects with at least one fall in the past 12 months were considered as fallers. LDE and variability were calculated from data of a trunk-mounted inertial-sensor collected during several minutes of treadmill walking. Maximal voluntary knee extension torque (MVT) was assessed isometrically.

Fall history was an effect modifier in the association between LDE and FoF only, i.e. only subjects without fall history and a high LDE had a five times higher chance of reporting FoF. Gait variability was not associated with FoF. Low MVT was associated with FoF. Multivariate analysis demonstrated that LDE was more strongly associated with FoF than MVT.

Decreased stability of gait as reflected in a high LDE and low muscle strength are associated with and a potential cause of FoF in subjects without fall history.

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## 1. Introduction

Fear of falling (FoF) frequently leads to activity restriction resulting in decreased quality of life [1]. FoF is also associated with fall risk [2]. However, the causal relationship between FoF and falling itself is not clear and can be bi-directional. FoF may be the result of a fall, but it may also increase falls risk. As people age, the

quality of gait becomes less because of negative changes in the neuromusculoskeletal system. The perceived loss of balance in static as well as dynamic situations in daily life, including possible near falls, may induce FoF. To develop interventions against FoF, knowledge about the associations between falling, FoF and the age-related changes in quality of gait is necessary.

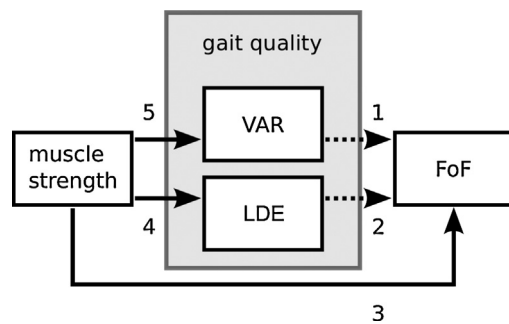
Age-related deterioration of gait quality is apparent in measures such as variability and local dynamic stability of trunk kinematics [3,4]. Variability in trunk kinematics during gait can be quantified by the standard deviation of trunk kinematics between strides. Local dynamic stability can be assessed by the local divergence exponents (LDE), which is quantified as the rate of divergence of the kinematics after very small, naturally occurring, variations [5]. A high LDE indicates fast divergence and hence low local dynamic stability. Generally, a high LDE and large variability of trunk kinematics in gait are indicators of a decreased gait quality [6–10]. Although gait variability is associated with falls risk [8,9],

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**Fig. 1.** Conceptual model of the associations (numbered 1–5) proposed in the introduction. VAR is variability; LDE is local divergence exponent; FoF is fear of falling. Solid lines indicate confirmed associations, dotted lines indicate unconfirmed associations.

an association with FoF could not be confirmed (Fig. 1, association 1) [8,9,11]. Also LDE is associated with fall risk [10,12], but, to the best of our knowledge, the association between LDE and FoF has not yet been investigated (Fig. 1, association 2). It is conceivable that the association of gait variability and LDE with FoF differs between subjects with and without fall history, as in fallers FoF is probably strongly determined by (the consequences of) recent falls.

Aging is associated with decreased muscle strength, and decreased muscle strength has been associated with FoF in adults over 70 years [2] (Fig. 1, association 3). In addition, decreased leg strength has been associated with gait variability in adults over 70 years [8,13,14] and with LDE in a study with young and elderly subjects [15]. However, associations of muscle strength with variability and LDE of trunk kinematics in gait (Fig. 1, associations 4–5) in older adults have not been reported.

The first aim of this study was to determine whether the variability and the LDE of trunk kinematics in gait and leg muscle strength are associated with FoF (Fig. 1, associations 1–3) in healthy older adults. The second aim was to assess whether leg muscle strength is associated with the variability and LDE of trunk kinematics during gait (Fig. 1, associations 4–5).

An association between gait characteristics and FoF may indicate that changes in gait quality induce FoF. If so, FoF could in part be caused by gait changes and in part be remedied by interventions that target the underlying physical causes rather than FoF itself. We targeted healthy adults from 50 years and older, to obtain a sample with a wide range in gait characteristics and muscle strength, including individuals with FoF but no history of falls. We hypothesized that high variability and LDE of trunk kinematics during gait are associated with FoF in non-fallers, but not in fallers. Moreover, we hypothesized that leg muscle strength is associated with a high variability and LDE of trunk kinematics during gait.

## 2. Methods

### 2.1. Participants

Subjects were recruited and tested at a national fair aimed at people of 50 years and older. Subjects were included if they were aged between 50 and 75 years and able to walk on a treadmill without walking aids. All subjects signed informed consent. The ethics committee of the Faculty of Human Movement Sciences, VU University Amsterdam, approved the experimental protocol, which was in accordance with the declaration of Helsinki.

### 2.2. Experimental protocol

Subjects walked for 12–17 min on a treadmill at 1.1 m/s. The first 5–10 min were used to become familiar with treadmill

walking. During the final 7 min, trunk accelerations and angular velocities were recorded at 100 Hz using an inertial sensor (Dynaport Hybrid, McRoberts B.V., The Hague, The Netherlands). The sensor was strapped to the back, just below the shoulder blades, as trunk control is critical for gait stability [16]. Sensor axes were aligned with the anatomical axes of the trunk in upright stance.

Maximal isometric voluntary knee extension torque (MVT) of the right leg was measured, while the subjects were seated on a custom made dynamometer with hip and knee joints fixed at an angle of 90°. The lower leg was strapped to a force sensor 0.245 m below the knee joint. Subjects were asked to provide as much force as possible for approximately 3 s. The subjects performed three MVT trials with verbal encouragement, separated by 1 min rest. If the final MVT exceeded the previous values by more than 10%, an additional trial was performed. The subjects received online visual feedback, on whether their attempt was higher or lower than the previous MVT. If a subject was unable to perform the MVT assessment with the right leg, the measurement was performed on the left leg (8 out of 130 subjects).

FoF was assessed by asking the subjects to rate their FoF when they performed activities of daily living on a 10-point numerical rating scale (1 = no fear at all, 10 = extremely fearful). A systematic review on psychological outcomes of falling showed that single-item questions are regularly used and, though only limited data are available, clinimetric properties are good [17]. For the question used in the present study, the validity and reliability are reported to be moderate to fair [18]. Fall history was obtained by self-report of number of falls in the last year. A subject was classified as a faller if at least one fall had occurred in the past 12 months. Subjects were classified as experienced treadmill walkers if they had walked on a treadmill at least twice before the measurements.

### 2.3. Data analysis

Before calculating MVT, the force data of the time series of all MVT trials were filtered using a 4th order Butterworth 150 Hz low-pass filter. The MVT was defined as the maximum of the filtered force signal multiplied by the moment arm (0.245 m) and divided by body mass [19].

3D trunk accelerations and angular velocities were analyzed in the sensor coordinate system, which was approximately aligned with the global coordinate system [20]. The final 150 strides were used to calculate gait parameters. Foot contacts were estimated based on the anterior-posterior acceleration signal for all gait parameters [21]. In short, after low-pass filtering of the AP acceleration signal (20 Hz, 4th order Butterworth), zero-crossings were determined and subsequently the peak forward acceleration preceding the zero-crossing was taken as the instant of foot contact. This method has been shown to yield a systematic offset, which does not affect the present analysis, and a small random error in comparison to foot contact detection using ground reaction forces [21].

To quantify variability and local dynamic stability of trunk kinematics during gait we used the variability of medio-lateral (ML) trunk acceleration and the LDE of the 3D trunk angular movement, respectively. In a factor analysis on a range of gait measures, these measures showed the highest factor scores within the clusters of gait parameters reflecting variability and stability respectively [10]. Gait variability was assessed by the standard deviation of ML trunk accelerations between strides ( $VAR_{ML}$ ). The ML acceleration data were low-pass filtered (20 Hz, 4th order Butterworth). Based on foot contact data, each of 150 strides was time normalized (0–100%). At each of the 100 normalized time points the standard deviation of the ML trunk acceleration over the 150 strides was calculated. Subsequently, the mean standard

deviation of these 100 standard deviations was calculated to determine  $VAR_{ML}$  [22].

For the analysis of local dynamic stability, the trunk kinematics were described in a 6D state-space reconstruction based on the three angular velocity time-series and one time-delayed embedded copy of each. A delay of 10 samples was used, which was the median value of the minimum of the mutual information function across all data. The dimensionality of 6 was found to be sufficient based on Global False Nearest Neighbor analysis. Local dynamic stability was quantified by the LDE, which describes how small initial differences in kinematics develop over the course of a step. For calculating the LDE, Rosenstein's algorithm was used [23] following procedures described previously [5,24]. Briefly, the kinematic data of 150 strides were resampled to 15,000 samples (100 samples per stride on average) preserving differences in stride time between strides [24,25]. For each point in state-space, a nearest neighbor was found and the Euclidean distance between these points was tracked for four strides resulting in as many time-distance curves as time points in state-space. The divergence curve was calculated as the mean of the natural log of the time-distance curves. The LDE was calculated as the slope of a linear fit to the first 50 samples (time needed for 1 step) of the divergence curve. Thus, the LDE indicates the relative rate of divergence over 1 step, resulting from a small difference in initial conditions. A positive LDE indicates local instability, i.e. after a small perturbation the states initially diverge. Obviously this reflects initial divergence and, hence, local instability does not equate to falling, but empirically higher LDE values are associated with falls risk [10,12].

All calculations were performed with custom written Matlab 7.6 (The MathWorks, Inc. Natick, MA) scripts.

## 2.4. Statistical analysis

All data were checked for normality of their distributions by exploring histograms,  $q-q$  plots, boxplots, normality tests and  $z$ -values of skewness and kurtosis. Distributions of  $VAR_{ML}$ , LDE and MVT appeared to be positively skewed. The outcome variable FoF was also not normally distributed. Within the range of possible scores for FoF (1–10 points) more than 50% of the participants scored 1 (median = 1, range = 1–7). The ratio properties of this variable are questionable. Therefore, we decided to dichotomize FoF at the median score, resulting in participants that were assigned to have no FoF (scores = 1) and participants that were assigned to have FoF (scores > 1). Consequently, associations of independent variables with the dichotomous dependent variable FoF were analyzed by logistic regression. Age, gender, body-mass index (BMI), and treadmill experience were considered as potential confounders in the associations studied and considered to be a confounder if they were significantly associated with both the independent and the dependent variable in the univariate models (models described below).

To answer the first research question, whether  $VAR_{ML}$ , LDE, and MVT are associated with FoF (Fig. 1, associations 1–3), logistic regression was performed. To avoid the assumption of linearity,  $VAR_{ML}$ , LDE, and MVT were dichotomised. As there are no normative data available for these variables are, the cut points used were their median values: 0.058  $m/s^2$ , 1.04, and 1.70 Nm/kg respectively. The univariate associations of these variables with FoF were assessed and additionally checked for effect modification by fall history. Fall history was regarded as an effect modifier if the interaction between the independent variable and fall history was significant, in which case the stratified analysis was leading in the interpretation of the results. The statistical models were checked for confounding by the potential confounders identified. If multiple significant univariate logistic associations were found, multivariate models were used to determine which variables were most

**Table 1**

Subject characteristics expressed as mean (SD), classification count (percentages), or median (range).

Characteristic		N
Age (years)	62.4 (6.2)	134
Gender (male/female)	49/85 (36.6%/63.4%)	134
BMI ( $kg/m^2$ )	25.2 (2.7)	134
Fall history (yes/no)	44/90 (32.8%/67.2%)	134
Treadmill experience (yes/no)	56/75 (42.7%/57.3%)	131
$VAR_{ML}$ ( $m/s^2$ )	0.064 (0.023)	132
LDE	1.04 (0.11)	132
MVT (Nm/kg)	1.81 (0.57)	130
Fear of falling	1 (1–7)	132

BMI is body-mass index;  $VAR_{ML}$  is spatial gait variability of medio-lateral trunk acceleration; LDE is local divergence exponent of angular velocities; MVT is maximal voluntary torque normalized to body mass.

strongly associated with the dependent variables. The overall fit of logistic regression models were quantified by Nagelkerke's  $R^2$  ( $R_N^2$ ), which can be interpreted as  $R^2$  in linear regression [26].

To test the second research question, whether MVT is associated with  $VAR_{ML}$  and LDE (Fig. 1, associations 4–5), linear regression was applied to the undichotomized, log transformed  $VAR_{ML}$ , LDE, and MVT, following the procedure as described for the first research question. The overall fit of linear regression models were quantified by  $R^2$ .

R 2.13 [27] was used for statistical analyses. Statistical significance was declared if  $p < 0.05$ .

## 3. Results

In total, 134 subjects, of which 85 were females, participated in this study. Subject characteristics are described in Table 1.

### 3.1. Univariate associations with FoF (associations 1–3, Fig. 1)

Fig. 2 illustrates the distributions of MVT, LDE and  $VAR_{ML}$  for subjects with and without FoF. Associations between the dichotomized predictor variables  $VAR_{ML}$ , LDE, and MVT and the dichotomized FoF are shown in Table 2.  $VAR_{ML}$  and FoF were not associated and no effect modification by fall history was observed ( $p = 0.591$ ). In the association between LDE and FoF, fall history was identified as an effect modifier ( $p = 0.006$  for the interaction effect). In the subsequent stratified analyses, subjects without fall history in the “high LDE” group were 5.13 times more likely to be in the group with FoF. In subjects with fall history, there was no association between LDE and FoF. The association between MVT and FoF was not modified by fall history ( $p = 0.659$ ). The univariate analyses between the predictor variable MVT and outcome variable FoF demonstrated that subjects in the “low strength” group were 2.17 times more likely to be in the FoF group.

### 3.2. Multivariate associations of MVT and LDE with FoF (associations 2–4, Fig. 1)

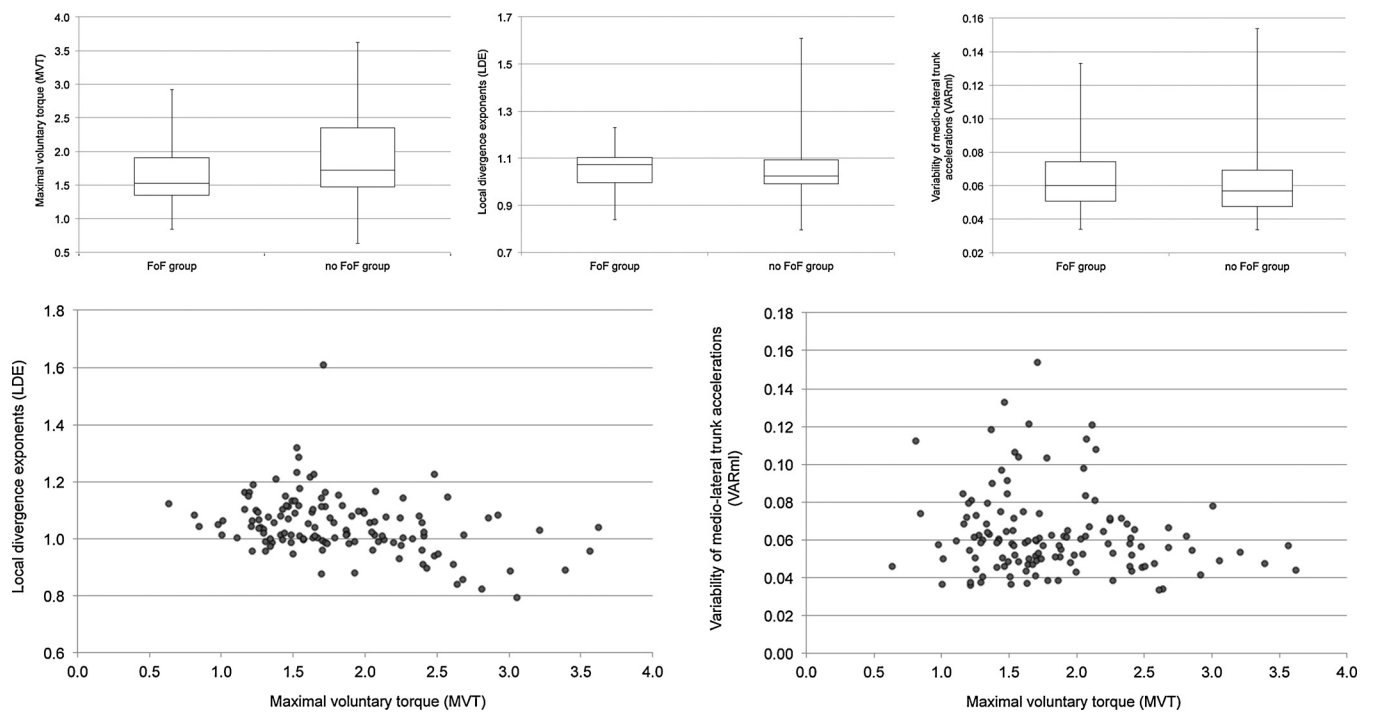
In the multivariate analyses with dichotomized MVT and LDE as predictor variables (Table 2), “high LDE” was significantly associated with the outcome variable FoF. When the analyses were performed for subjects with fall history and subjects without fall history separately, this association was significant in subjects without fall history, showing a relatively large effect size (OR = 4.57) and absent in subjects with fall history. MVT, corrected for LDE, was not associated with FoF.

### 3.3. Associations between MVT, $VAR_{ML}$ and LDE (associations 4 and 5, Fig. 1)

Fig. 2 shows the individual values of MVT in relation to  $VAR_{ML}$  and LDE. Univariate linear regression analysis showed no significant association between MVT and  $VAR_{ML}$ . Higher muscle strength was significantly associated with lower LDE in a univariate analysis, but this association disappeared after correcting for confounding by age and gender (Table 3).

## 4. Discussion

The first aim of this study was to determine whether  $VAR_{ML}$ , LDE, and leg muscle strength are associated with FoF. The results of this study demonstrate that non-fallers with high LDE, i.e. a more unstable gait pattern, had more FoF than non-fallers with low LDE. How subjects perceive the stability of their gait pattern may have commonalities with the LDE and may be incorporated in their FoF



**Fig. 2.** Overview of the data, with boxplots, showing the distributions of maximal voluntary torque (MVT), spatial gait variability of medio-lateral trunk acceleration ( $VAR_{ML}$ ) and local divergence exponents (LDE) for subjects with and without fear of falling (FoF), and scatterplots showing the relation between individual scores of MVT with those of  $VAR_{ML}$  and LDE.

appraisal. The association between LDE and FoF was not found for subjects with a fall history. In agreement with previous studies, we found that  $VAR_{ML}$  was not associated with FoF [8,9,11]. It has been argued that gait variability may not be a suitable measure to describe (gait) stability [22]. However, it is associated with falls risk [8,9] as is the LDE [10,12]. It is at present unclear why only LDE is associated with FoF.

Subjects with lower muscle strength reported FoF, as was reported previously [2]. It has been suggested that limitations experienced during activities of daily living are caused by low muscle strength and as such cause FoF [2]. MVT might be directly associated with gait quality (association 3, Fig. 1). However, the multivariate analyses demonstrated that LDE was more strongly associated with FoF than MVT. In combination with the association

between MVT and LDE, this suggests that MVT may be associated with FoF through its effect on gait stability (associations 4 and 2, Fig. 1). The association between MVT and LDE disappeared after correcting for age and gender. A possible explanation for this is that higher age and female gender partly determine muscle strength, which in turn affects gait stability, while age and gender also have an independent effect on gait stability.

FoF might be a target for intervention given its effects on quality of life [1]. On the other hand, FoF is associated with fall history [2] and here it was shown that it is related to low muscle strength and reduced local dynamic gait stability. Therefore, improving physical abilities by, for example, strength and gait training might be an appropriate way of targeting FoF and at the same time reducing fall risk.

**Table 2**

Odds ratios for low gait quality (high  $VAR_{ML}$  and high LDE) and low muscle strength (MVT) in univariate associations (logistic regression), and low MVT and high LDE in multivariate associations (logistic regression) with fear of falling (FoF), also stratified for fall history. The reference value of the logistic regression is always the same (with OR = 1.00).

Model	Predictor	Stratum	OR <sup>a</sup>	95% CI <sub>OR</sub>	R <sub>N</sub> <sup>2</sup>
Univariate	$VAR_{ML}$	–	1.82	0.89–3.80	0.03
		Non-fallers	1.43	0.57–3.56	0.01
		Fallers	2.25	0.59–9.82	0.04
Univariate	LDE	–	0.56	0.16–1.91	0.03
		Non-fallers	<b>5.13</b>	<b>1.99–14.3</b>	0.17
		Fallers	0.56	0.16–1.91	0.03
Univariate	MVT	–	<b>2.17</b>	<b>1.06–4.55</b>	<b>0.05</b>
		Non-fallers	2.44	0.98–6.25	0.06
		Fallers	1.72	0.51–5.88	0.02
Multivariate: MVT+LDE	MVT	–	1.89	0.90–4.00	0.09
	LDE	–	<b>2.14</b>	<b>1.01–4.59</b>	
	MVT	Non-fallers	1.82	0.68–5.00	0.19
	LDE	Non-fallers	<b>4.57</b>	<b>1.73–12.9</b>	
	MVT	Fallers	1.92	0.55–7.14	0.06
	LDE	Fallers	0.50	0.13–1.80	

$VAR_{ML}$  is variability of medio-lateral trunk acceleration; LDE is local divergence exponent of trunk angular velocities; MVT is maximal voluntary torque; OR is odds ratio; 95% CI<sub>OR</sub> is the 95% confidence interval of OR; R<sub>N</sub><sup>2</sup> is explained variance (Nagelkerke's R<sup>2</sup>).

<sup>a</sup> ORs are crude ORs as confounding was not present.



**Table 3**

Results of linear regression with maximal voluntary torque (MVT) as predictor with variability of medio-lateral trunk accelerations ( $VAR_{ML}$ ) and local divergence exponent of trunk angular velocities (LDE) as dependent variables.

Predictor	Stratum	Confounder	B	95% CI <sub>B</sub>	R <sup>2</sup>
MVT	–	$VAR_{ML}$	–0.03	–0.07 to 0.01	0.02
		LDE	–0.06	–0.09 to –0.03	0.12
MVT	–	Age + gender	–0.01	–0.06 to 0.03	0.20

$VAR_{ML}$  is variability of medio-lateral trunk acceleration; LDE is local divergence exponents of trunk angular velocities; MVT is maximal voluntary torque; B is unstandardized regression coefficient; 95% CI<sub>B</sub> is the 95% confidence interval of B; R<sup>2</sup> is explained variance.

The study population consisted of older adults of 50–75 years of age from all over the country that attended a national fair and voluntarily participated in the measurement sessions. Thus, this study population may be relatively active and healthy with a relatively low FoF and may not be representative of all older adults between 50 and 75 years. This is reflected in the median score of FoF of 1 with a range of 1–7 on a 10-point scale with more than 50% of the subjects having a score of 1, possibly related to the relatively young mean age of the participants (62 years) in comparison with previous studies (over 80 years [9,11]). Nevertheless, the subtle difference in FoF between groups was large enough to demonstrate that LDE was associated with FoF in subjects without fall history. Nevertheless, our results likely present an underestimation when considering the overall population of people over 50 years, which likely has a wider distribution of LDE, MVT and FoF.

In conclusion, the results suggest that decreased stability of gait, as reflected in a high LDE in subjects without fall history, and low MVT, are associated with and a potential cause of FoF. This indicates that interventions aimed at improving leg muscle strength and quality of gait in older adults could be effective in reducing FoF, as well as the risk of falling.

### Conflicts of interest statement

The authors declare that there are no conflicts of interest.

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